Internal Waves in the Vicinity of the Kuroshio Path

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LONG-TERM GOALS

My long-term scientific goals are to understand the dynamics of small-scale processes and to quantify the mechanisms by which mixing occurs in the ocean and thereby help develop improved parameterizations of mixing for ocean models. Mixing within the stratified ocean is a particular focus as the complex interplay of internal waves from a variety of sources and turbulence makes this a current locus of uncertainty. A better understanding of energy sources and the dynamics of internal waves will help improve a physics-based parameterization scheme for ocean models.

OBJECTIVES

For this project, our broad focus is on inertial waves, internal tides, internal wave continuum, and nonlinear internal waves in a complex and diverse dynamic environment (Fig. 1) where the Kuroshio interacts with the shallow and the deep topography (Tang et al., 2000), strong nonlinear internal waves and finescale inertial shear layers are observed (Rainville and Pinkel, 2005), and strong internal tides have been suggested by numerical models (Niwa and Hibiya, 2004). Primary objectives of this project are 1) to provide a geographical map and the long-term variation of internal wave energy and shear variances, 2) to quantify high-frequency nonlinear internal wave energy, and 3) to quantify energy and shear of inertial waves along the Kuroshio path.

APPROACH

We will analyze observations taken in the vicinity of the Kuroshio Path from the Luzon Strait to the southern East China Sea. Available data sets include 1) moored and bottom mounted ADCPs, and shipboard ADCP observations, 2) CTD profiles, 3) moored temperature 4) moored current meter data, and 5) echo sounder data. Previous studies of these data focused primarily on sub-inertial processes. Most of available data were taken at a sampling rate of < 60 minutes, suitable for studying internal waves.

WORK COMPLETED

We perform analysis of a set of three ADCP mooring measurements taken in a cross section on the Kuroshio path (Fig. 2). A preliminary analysis of historical CTD data is made to identify water mass properties at three stations. We quantify energy and shear variance in various internal wave frequency regimes and look for similarity and differences within and off the Kuroshio.

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RESULTS

We analyze measurements taken from three ADCP moorings off the east coast of Taiwan, K1, K2, and K3 (Fig. 2). These measurements were taken as a part of the Kuroshio Upstream Dynamics Experiment. We first perform the water mass analysis at three stations. The water mass east of Philippine is often defined as the Kuroshio water (black block in Fig. 2), and the water mass west of Philippine is often defined as the South China Sea water (red block in Fig. 2) (Chern and Wang, 1998). In our analysis, we will call them east Philippine water (EP) and west Philippine water (WP), respectively.

Liang et al. (2003) define the Kuroshio flow when the northward sub-tidal low-frequency velocity off the east coast of Taiwan exceeds 0.1 m s-1. Temporal and vertical variations of velocity components and vertical shear at three stations are illustrated in Figs. 3-5. Following Liang et al. (2003), we define the Kuroshio when the sub-tidal northward velocity averaged in the upper 200 m exceeds 0.1 m s-1. Station K1 is often outside of the Kuroshio path (Fig. 3), station K2 is *always* on the main Kuroshio path (Fig. 4), and station K3 is often on the Kuroshio path (Fig. 5). Low-frequency velocity plots are not shown. T-S properties of water masses at stations K1, K2, and K3 are shown in Fig. 6. They are compared with those of EP and WP (Chern and Wang, 1998). T-S distribution of the water mass at station K2 lies between those of EP and WP. Intuitively we believe that the water mass at station K2 is a mixture of waters at EP and WP; strong mixing occurs in the 200-km Kuroshio path between the Luzon Strait and station K2. A better understanding the dynamics of responsible turbulent processes is needed to quantify the mass, heat, momentum, and energy transports of the Kuroshio. The water mass properties at station K3 are closer, but not identical, to those of EP, and the water mass properties at station K1 are closer, but not identical, to those of WP.

Chern and Wang (1998) show that off the east coast of Taiwan the Kuroshio has two cores of maximum velocity. They propose that two water masses, EP and WP, merge into the Kuroshio. However, the dynamics of the merging mechanisms is not known. A conventional flow path of the Kuroshio is as follows. The Kuroshio passes the east of Philippine, flows northward by the Luzon Strait or intrudes into the Luzon Strait and South China Sea depending on seasons, and flows prevailingly northward off the east coast of Taiwan. This conventional view can not explain the two velocity cores within the Kuroshio found by Chern and Wang (1998). Also, this conventional view suggests that the water mass in the Kuroshio originates mostly from EP. However, our T-S analysis results show that the water mass at station K2 in the main path of the Kuroshio is a near 50-50 mixture of water masses at EP and WP. Clearly, the conventional view of the Kuroshio path from the east Philippine to the east coast of Taiwan requires further verification.

We examine energy of internal waves within and off the Kuroshio. ADCP velocity measurements taken during the period between Dec. 12, 2001 and Jan. 1, 2002 are analyzed. In this period, station K1 is outside of Kuroshio path. Both stations K2 and K3 are on the Kuroshio path. We are particularly interested in high-frequency internal waves that contain most of vertical shear variances. For all stations, the horizontal kinetic energy of high-frequency internal waves is a factor of 2-5 greater than the prediction of GM (not shown) suggesting possible sources of internal waves on the Kuroshio path.

At 100-m depth, clockwise rotary spectra of the vertical shear of horizontal velocity at stations K1, K2, and K3 are shown in Fig. 7a. At station K1, i.e., within the Kuroshio, clockwise shear variances at diurnal, semidiurnal and super-tidal frequencies are the strongest. At station K2, i.e., off the Kuroshio, they are the weakest. This is better shown in vertical profiles of the super-tidal clockwise shear

variances (Fig. 7b). At depths greater than 90 m, the super-tidal clockwise shear variance at station K1 is much greater than those at stations K2 and K3. Note that clockwise shear variances are generally greater than counterclockwise shear variances at these stations and at most depths. The source of the extra super-tidal shear variances at K2, within the Kuroshio, requires further investigation. The dynamic roles of super-tidal shear variances in mixing EP and WP, and within the Kuroshio are important for understanding the mass, heat, momentum, and energy budgets of the Kuroshio. We will continue the present analysis and extend the analysis to measurements taken in the Luzon Strait and north of stations K1, K2, and K3, to map internal wave energy and shear variances along the Kuroshio path.

IMPACT/APPLICATION

The mass, heat, momentum, and energy transports of Kuroshio are potentially important for modulating Asian waters. To improve our skill of modeling turbulent processes and quantifying turbulence mixing within the Kuroshio and between the Kuroshio and surrounding water we need to identify energy sources of internal wave and turbulence mixing along the Kuroshio path. Results of the present analysis of historical data will provide the spatial and temporal distributions of internal wave energy and shear variances along the path of the Kuroshio and improve our understanding of the Kuroshio dynamics.

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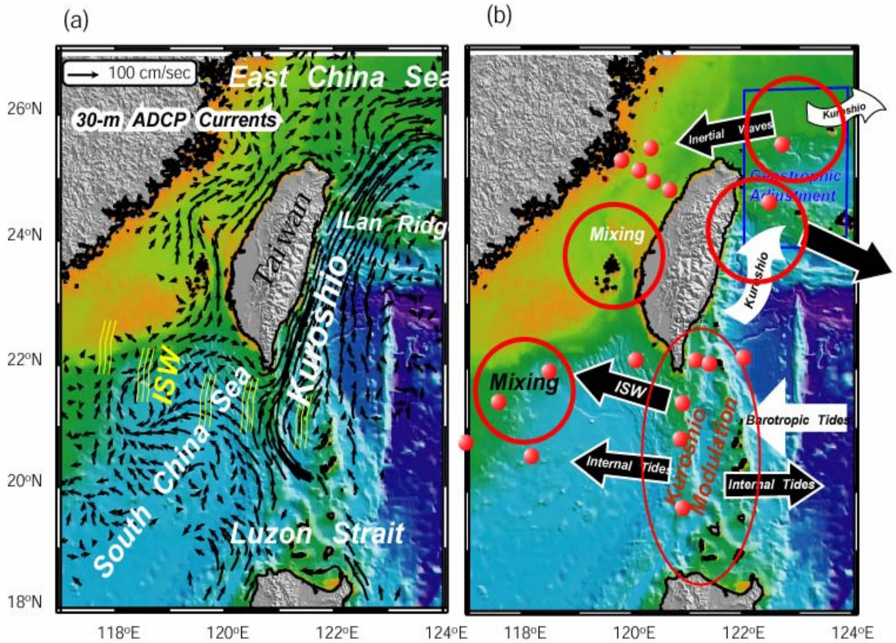

Figure 1: (a) Topography of western Pacific near Taiwan. Composite shipboard ADCP velocity at 30-m depth (figure adopted from Liang et al. 2003) shows Kuroshio crossing regions of strong topography in Luzon Strait and impinging on the continental shelf of the East China Sea northeast of Taiwan. (b) Potential small-scale processes in the region. Potential hot spots for generation of internal waves and turbulence mixing are red circled in (b). Red bullets mark positions of available mooring data for the present analysis.

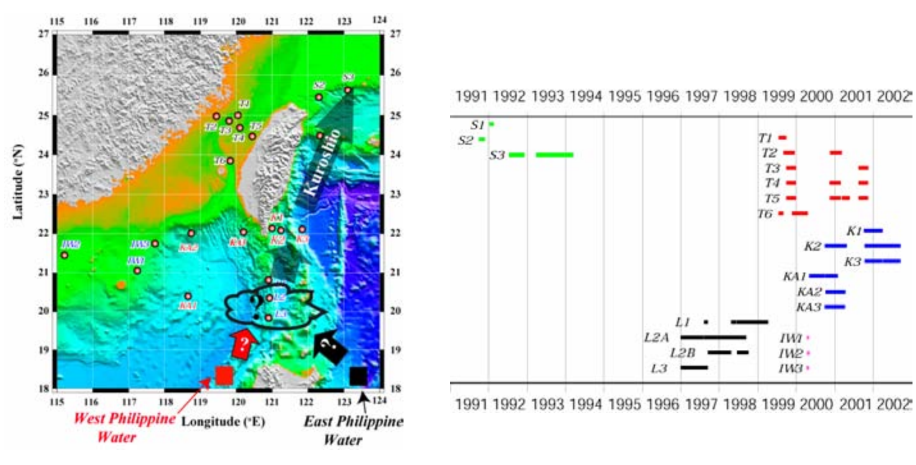

Figure 2: Positions (left panel) and periods (right panel) of moored ADCPs and current meters in ECS, Taiwan Strait, Kuroshio, Luzon Strait, and SCS. Stations of current meter and ADCP moorings are labeled. Red and Black blocks represent the area where water masses are commonly defined as South China Sea Water and Kuroshio Water, respectively. We emphasize in our analysis that this definition is misleading and term them as west Philippine water and east Philippine water, respectively. In the main axis of the Kuroshio, e.g. station K2, the water mass is a mixture of these two water types.

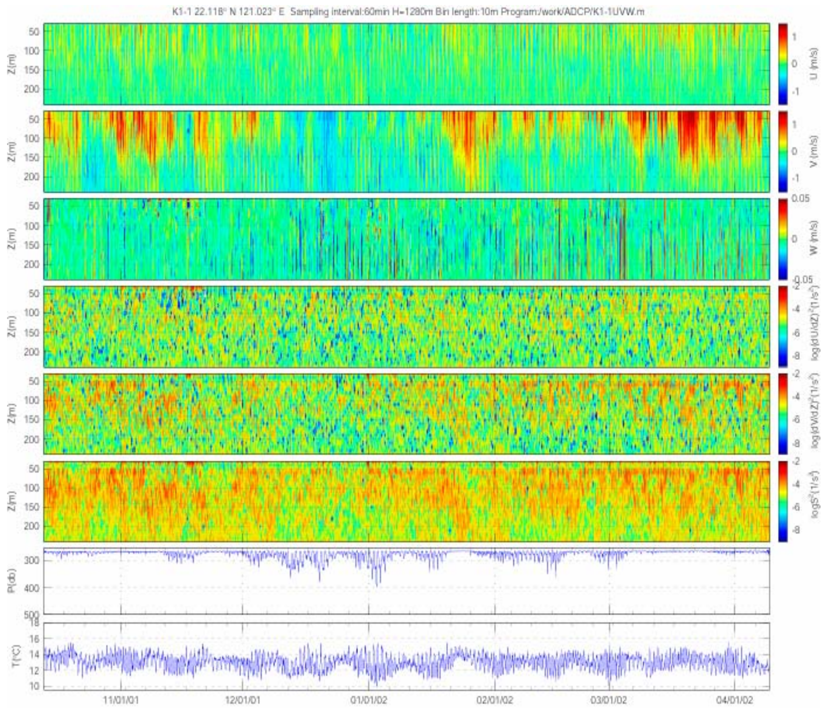

Figure 3: Depth-time variations of velocity and shear observed at station K1, and time series of temperature and pressure near the ADCP depth.

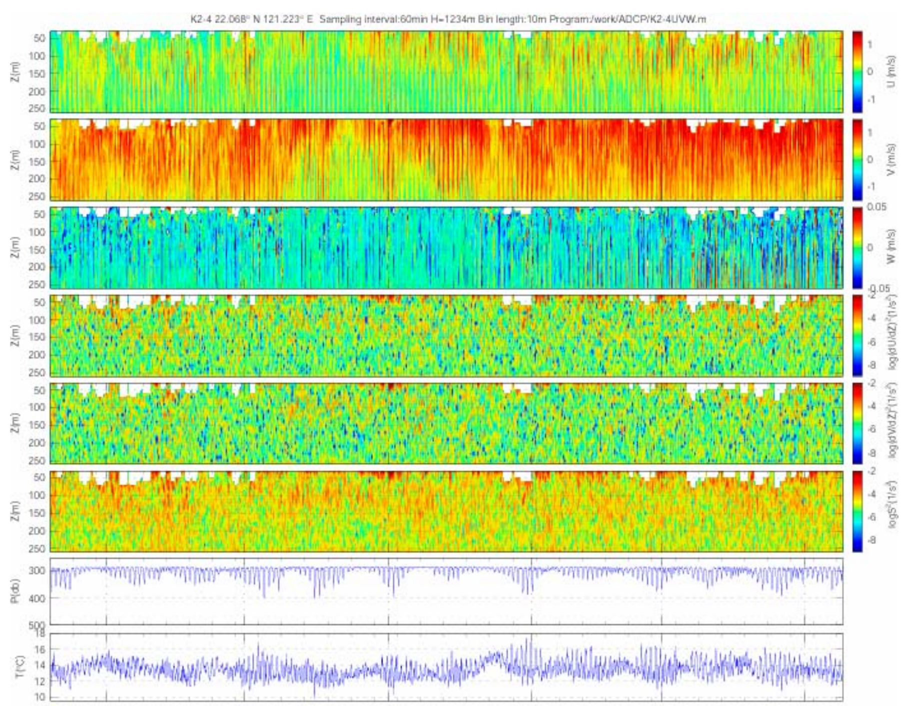

Figure 4: Depth-time variations of velocity and shear observed at station K2, and time series of temperature and pressure near the ADCP depth.

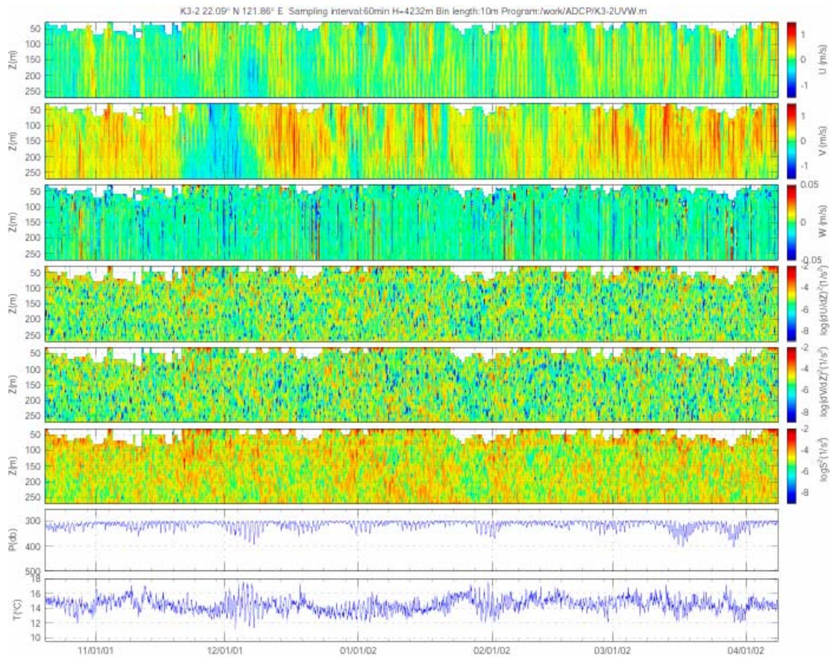

Figure 5: Depth-time variations of velocity and shear observed at station K3, and time series of temperature and pressure near the ADCP depth.

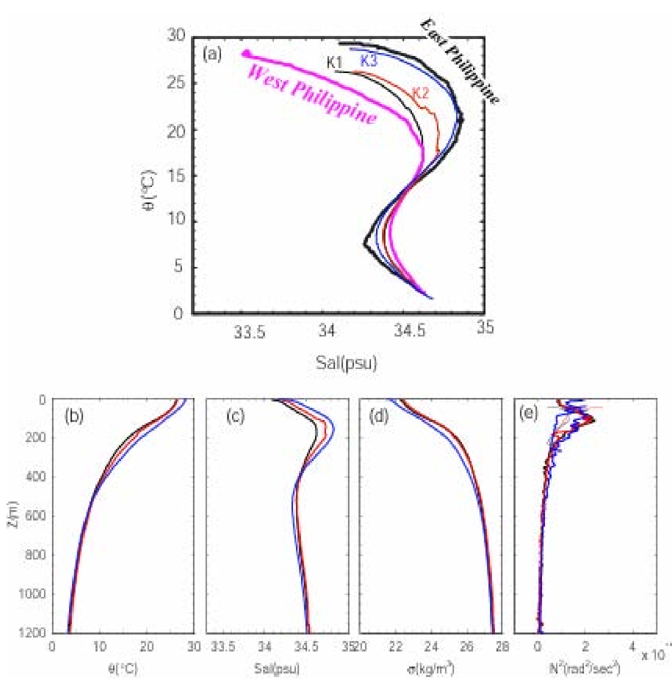

Figure 6: Water properties at three mooring positions, K1 (black), K2 (red), and K3 (blue). The panel (a) shows T-S properties of water masses at mooring stations, west of Philippine (magenta), and east of Philippine (thick black). Vertical profiles of potential temperature, salinity, potential density, and N2 are shown in panels (b), (c), (d), and (e).Thin curves in panel (e) are total shear squared computed from mooring ADCP data.

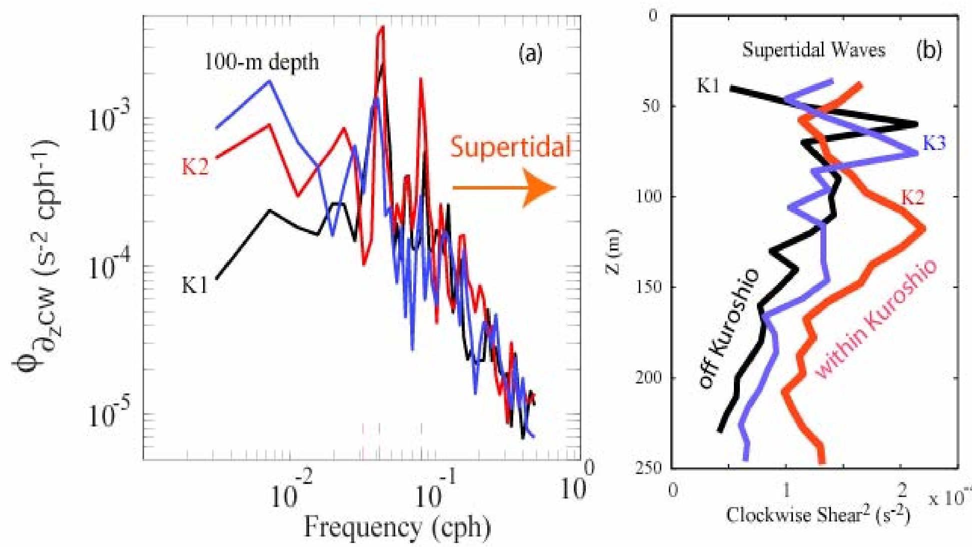

Figure 7: (a) Spectra of clockwise component of horizontal shear at 100-m depth, and (b) vertical profiles of clockwise component of horizontal shear variances at frequencies greater than the semidiurnal tide. Spectra and energy vertical profiles are computed using measurements taken between Dec. 12, 2001 and Jan. 1, 2002 when station K1 is off the Kuroshio path, and stations K2 and K3 are on the Kuroshio path. Station K2 is within the main axis of the Kuroshio.